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## Power Production Analysis of the OE Buoy WEC for the CORES Project

Lavelle, John; Kofoed, Jens Peter

*Publication date:*  
2011

*Document Version*  
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*

Lavelle, J., & Kofoed, J. P. (2011). *Power Production Analysis of the OE Buoy WEC for the CORES Project*. Department of Civil Engineering, Aalborg University. DCE Technical reports No. 119

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# **Power Production Analysis of the OE Buoy WEC for the CORES Project**

**J. Lavelle  
J. P. Kofoed**

**Carried out under contract for:**

**The CORES EU Project**

Coordinator:  
Hydraulics and Maritime  
Research Centre  
University College Cork





Aalborg University  
Department of Civil Engineering  
Wave Energy Research Group

**DCE Contract Report No. 119**

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by

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J. P. Kofoed

September 2011

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Published 2011 by  
Aalborg University  
Department of Civil Engineering  
Sohngaardsholmsvej 57,  
DK-9000 Aalborg, Denmark

Printed in Aalborg at Aalborg University

DCE Technical Report No. 119

## **Preface**

This report concerns the data analysis for the OE Buoy WEC, scale 1:4 model for the CORES EU project (EU project number 7<sup>th</sup> PQ RTD EU).

The WEC was tested in March, April and May at Galway Bay. The data was analysed in order to evaluate its wave-to-wire power production performance.

### **Contact information:**

Associate Professor Jens Peter Kofoed  
Department of Civil Engineering  
Aalborg University  
Sohngaardsholmsvej 57  
9000 Aalborg  
Denmark

Email: [jpk@civil.aau.dk](mailto:jpk@civil.aau.dk)  
Telephone: +45 9940 8474

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Dr John Lavelle  
Department of Civil Engineering  
Aalborg University  
Sohngaardsholmsvej 57  
9000 Aalborg  
Denmark

Email: [jlav@civil.aau.dk](mailto:jlav@civil.aau.dk)  
Telephone: +45 9940 8578



## Contents

Preface .....	1
1.1    Introduction .....	5
1.2    Power Production Estimation .....	6
1.3    Conclusion .....	11
Bibliography.....	12
Appendix 1 .....	13
Appendix 2.....	14





## 1.1 Introduction

This report describes the analysis performed on the OE Buoy for the CORES project by the wave energy group at Aalborg University, Denmark.

OE Buoy is a type of Oscillating Water Column (OWC) wave energy converter as part of the CORES project. This type of device is one of the most developed to extract energy from the ocean (1). Typically, a Wells turbine is used for the Power Take Off (PTO) for OWCs. The Wells turbine has the advantage that it is self-rectifying – with the ability to operate with either direction of airflow, which changes during each cycle of the wave. This type of turbine, however, suffers from the occurrence of sudden stops (2). Another type of self-rectifying turbine, an impulse turbine, was used in place of a Wells turbine to, in refit of the OE Buoy, in order to compare the two types.

OE Buoy was deployed in Galway Bay, Ireland during March, April and May of 2011, during which a total of 39 hours of power production data was collected. A data acquisition system was used to sample the sensors on board and the generator shaft power time-series data was used in the analysis here. A wave-rider buoy, located at the site of OE Buoy and operated by the Marine Institute Ireland, was used to determine the wave statistics for the sea conditions which coincided with the OE Buoy device data, in order to estimate the efficiency of the device as a function of the sea state (for example as a function of the mean zero down period,  $T_z$ , and, significant wave height,  $H_s$ ) as described below. This may then be used to estimate the yearly power production of the device at the test site location or another location, by using the long-term wave statistics for the given site. Additionally, the power production for a given scale of device may be estimated by applying the appropriate scaling to the efficiency function.

With sea trials – unlike wave tank testing – we are limited to testing in the sea states that happen to occur when the device is operational during deployment period. This can mean that efficiency data is sporadically distributed as a function of  $T_z$  and  $H_s$ , making it difficult to determine the efficiency function. The Equimar project deliverable 4.2 (3) describes a method for analysing and presenting the power production data in order to determine the yearly power production of the device at a given location and quantify its uncertainty. The limited amount of power production data meant that it was not possible to fully implement the method, as the efficiency data was too sparsely distributed as a function of  $T_z$  and  $H_s$ , but the method used here is based on the Equimar protocol to give an approximate estimate of the yearly power production.

## 1.2 Power Production Estimation

The power production time series of OE Buoy were analysed in order to estimate the yearly power production of the device at its location and the overall efficiency of the device.

The Yearly Power Production (YPP) of the full scale device is given by:

$$YPP = 24 \times 365 \times \sum_i \sum_j PM_{i,j} F_{i,j},$$

where  $PM_{i,j}$  is the power matrix and is given by:

$$PM_{i,j} = w \times Pw_{i,j} \times \eta_{i,j},$$

where  $w$  is the capture width of OE Buoy (6m),  $Pw_{i,j}$ ,  $\eta_{i,j}$  and  $F_{i,j}$  are arrays (of index  $i, j$ ) containing the power in the wave, the non-dimensional efficiency of OE Buoy, and the frequency of occurrence of the wave states at the given site,  $F$ , for intervals of significant wave height,  $H_s$ , and  $T_z$ .  $F_{i,j}$  is derived from buoy data. The centre values for each interval of  $H_s$  and  $T_z$  are used to generate  $Pw_{i,j}$ . The power, in Watts, contained in the waves,  $\overline{Pw(H_s, T_p)}$ , is calculated using the deep water approximation from:

$$Pw(H_s, T_p) \approx 493 \times H_s^2 T_e,$$

$$\text{where } T_e \approx 1.14 \times T_z,$$

by assuming a Pierson-Moskowitz spectrum.

Seventy-two time continuous time series of the power produced at the generator shaft, totaling 39 hours, were obtained during the testing campaign. These time series varied in length, but only those greater than 30 minutes were used to estimate the power matrix, giving 21 hours of data for use in the power production estimation. The power production time series' were divided in to 30 minute intervals and averaged to give 42 data points of the mean power production. 30 minute wave spectra, from a wave buoy recordings located at the site of OE Buoy WEC, were used to obtain the mean wave power,  $H_s$  and  $T_z$  of the waves per meter which coincided with the power production data. The wave power per meter was multiplied by the capture width,  $w$ , of the device to give the mean wave power incident on the device. The mean power production values were divided by the power of the waves incident on the device to give the non-dimensional efficiency.

Figure 1 shows the long probability of wave occurrence, derived from binned values of  $H_s$  and  $T_z$  from wave data records from the years 2006 and 2007, provided by HMRC. The values of  $H_s$  and  $T_z$  of the measured efficiency values are superimposed on this plot. The rectangular boxes show the zones used to determine the efficiencies. The efficiencies are approximated as constant values over the ranges of each box. The efficiency is calculated by averaging the top five values in each box and is given as a function of  $H_s$  and  $T_z$  in Figure 2. The efficiency of an OWC has a greater dependence on  $T_z$  than  $H_s$ , which is used to calculate the shape of the boxes. Choosing the number of data points to select in each zone in this way is a trade-off between uncertainty in the calculated power production values and rejecting points corresponding to suboptimal operation of the device. Generally at least

ten points per zone is desirable when calculating the efficiency of each these, but given the limited amount of data available, a lower threshold of five is used to give an approximate estimate of the power production. The efficiency function is used to calculate the power matrix given in Figure 3 and Table 2. The individual efficiency data points are given in Table 3.

The following parameters are evaluated and given in Table 1:

The Mean Wave Power, **P<sub>wave</sub>**, is given by:

$$\mathbf{P_{wave}} = \sum_i \sum_j P_{w_{ij}} F_{ij},$$

where  $i$  and  $j$  are the indexes of the array.

The Mean Mechanical Power is given by:

$$\bar{P} = \sum_i \sum_j PM_{ij} F_{ij}$$

The cell with the peak mechanical power is given by:

$$\mathbf{Peak\ P} = \max PM_{ij}.$$

The Load Factor is given by:

$$\mathbf{Load\ Factor} = \frac{\bar{P}}{GC},$$

where GC is the generator capacity.

The Overall Efficiency is given by:

$$\mathbf{Overall\ Efficiency} = \frac{\bar{P}}{w \times \mathbf{P_{wave}}}$$

Location	Test Site	EMEC
<b>Generator Capacity</b>	11 kW	
<b>P<sub>wave</sub></b>	3.4 kW/m	38.9kW/m
<b>Length</b>	6 m	24 m
<b>Overall Efficiency</b>	7.1%	5.2%
<b>YPP [MWh/Yr]</b>	12.7 MW·hr/yr	423.7 MW·hr/yr
<b>Peak P [kW]</b>	8.3 kW	1814.5 kW
<b><math>\bar{P}</math> [kW]</b>	1.45 kW	48.4 kW
<b>Load Factor</b>	13.2%	

**Table 1:** The estimated parameters relating to the power production for OE Buoy at its test location, in Galway Bay, and at the EMEC test location centre. The EMEC values should be treated with caution (see text). The generator capacity for EMEC is a design choice

It should be noted that the peak power is not the peak power encountered by the device during its operation, but is the cell in the power matrix with the maximum power, which is calculated by averaging the time series'. These values include any wave to wire losses, except parasitic losses due to the power required to move the guide vanes.

The yearly power production has been estimated for a full scale OE buoy, which is four times larger than the device tested at Galway Bay, with a capture width of 24 m. Figure 4 shows the estimated efficiency as a function of  $T_e$  and  $H_s$ , which scale with  $\sqrt{S}$  and  $S$  respectively, where  $S$  is the scale of the device (which in this case is 4). For the 1:4 scale device tested, the efficiency was very low in the region coinciding where most of the wave occur (shown enclosed by a white line in Figure 4) when scaled. This may be because the turbine needs to be above a certain threshold wave power before it starts to operation effectively – an effect which may not scale significantly. Considering this, the zones, over which the efficiency values are calculated, have been extended in order to cover the region where most of the waves occur at EMEC, despite the fact that low efficiencies were measured in this region for the tested device. The figures for EMEC, shown in Table 1, should therefore be treated with caution.

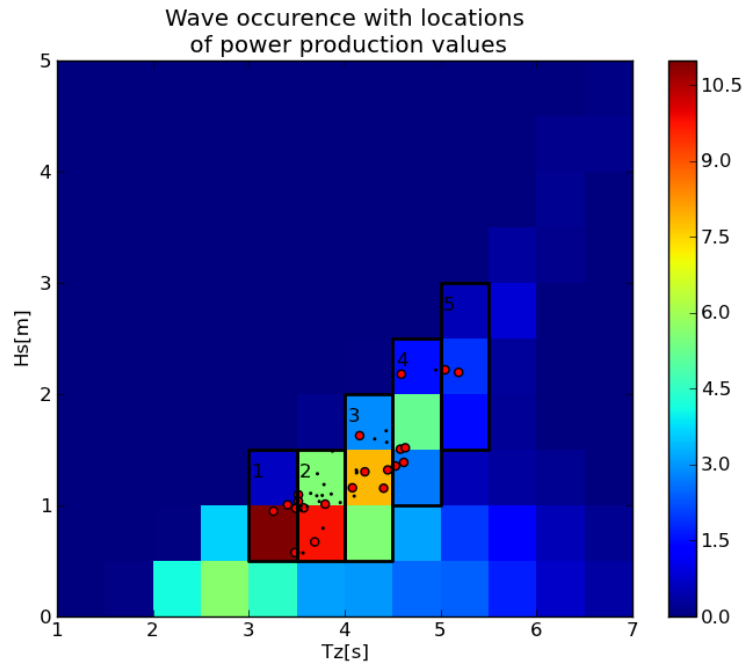


Figure 1: The percentage wave occurrence for binned intervals of  $H_s$  and  $T_z$ , with the locations of the measured power production values. The red dots are those that are used to calculate the yearly power production

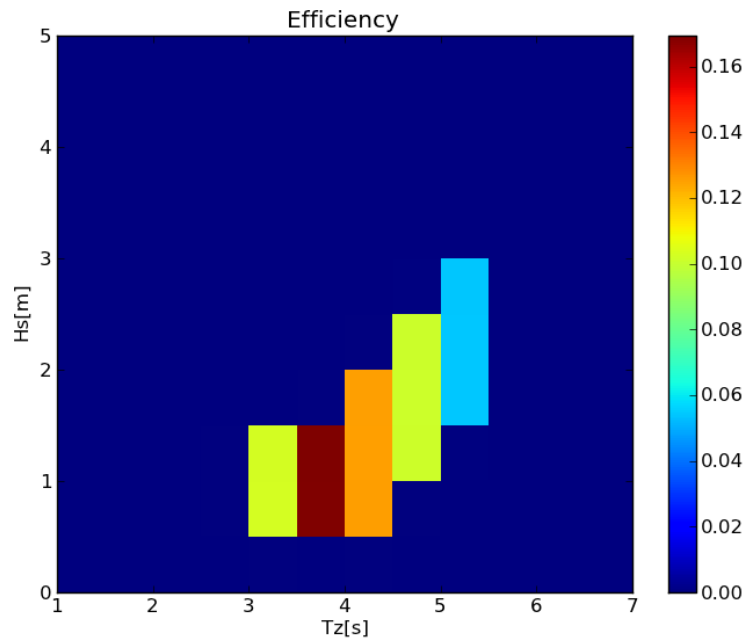


Figure 2: The estimated efficiency, given as a ratio, as a function of  $H_s$  and  $T_z$

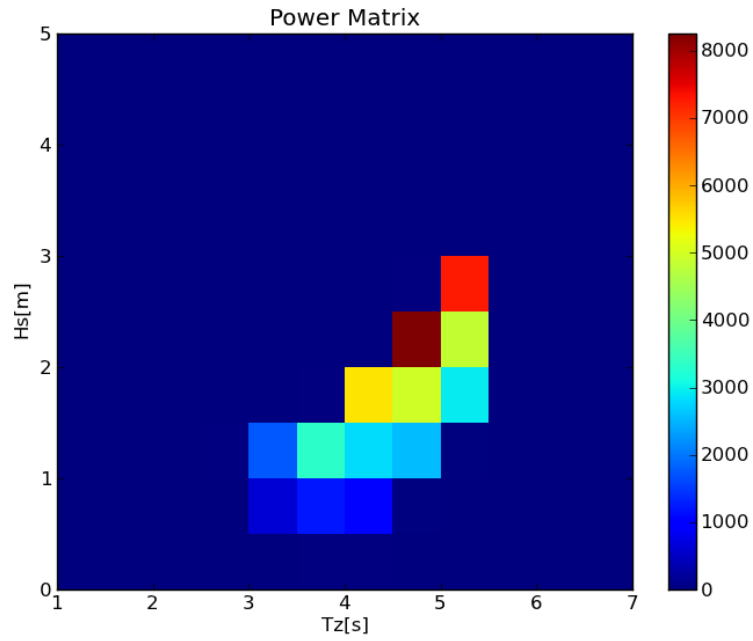


Figure 3: The power matrix of OEBuoy in Watts

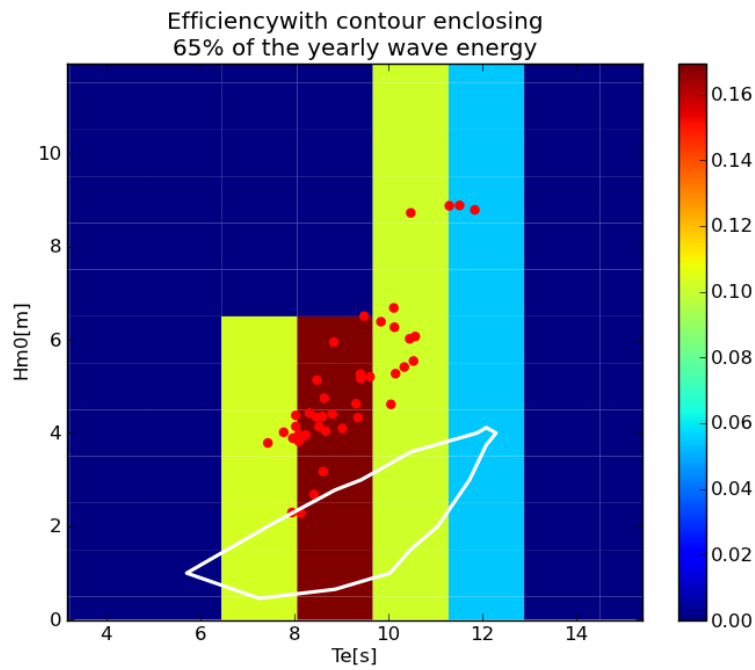


Figure 4: The estimated efficiency of a full scale OE Buoy (24 m wide) device, with the (scaled) data from which the efficiency is derived (shown as red points). The white circle encloses the region where 65% of the occur at the EMEC site, based on long term statistics.

### **1.3 Conclusion**

The estimated yearly power production of the OE Buoy at the test location was 12.7 MW·hr/yr with and peak efficiency was approximately 17%. These figures, however, should be treated with caution, due to the low number of data points used to estimate it.



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## Appendix 1

		Tz bin intervals [s]						
		[2.5,3)	[3,3.5)	[3.5,4)	[4,4.5)	[4.5,5)	[5,5.5)	[5.5,6)
Hs bin intervals [m]	[3.3,5)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	[2.5,3)	0.00	0.00	0.00	0.00	0.00	7.27	0.00
	[2,2.5)	0.00	0.00	0.00	0.00	8.25	4.87	0.00
	[1.5,2)	0.00	0.00	0.00	5.50	4.99	2.94	0.00
	[1,1.5)	0.00	1.76	3.35	2.81	2.55	0.00	0.00
	[0.5,1)	0.00	0.63	1.20	1.01	0.00	0.00	0.00
	[0,0.5)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

**Table 2: Power matrix in kW**

## Appendix 2

Hm0 [m]	Tz [s]	% Efficiency
0.57	3.57	10.38
0.57	3.48	8.95
0.67	3.69	15.88
1.5	4.58	10.59
1.52	4.63	11.71
1.39	4.62	12.94
1.32	4.45	13.94
1.35	4.53	12.7
1.15	4.41	16.36
1.08	4.1	8.75
1.1	3.86	7.96
0.79	3.77	8.04
1.02	3.95	13.77
1.01	3.8	16.42
1.03	3.74	11.22
0.99	3.61	9.03
0.96	3.55	10.34
0.99	3.54	2.25
1.11	3.65	7.2
0.98	3.57	17.2
0.97	3.49	12.86
1	3.4	14.76
1.09	3.52	15.2
1.04	3.52	19.96
1.29	4.12	5.63
1.3	4.13	6.95
1.3	4.21	9.42
1.32	4.12	8.18
1.16	4.08	12.88
2.2	5.19	2.1
2.22	5.05	8.76
2.22	4.95	2.21
2.18	4.59	2.94
0.95	3.26	4.52
1.63	4.16	10.03
1.09	3.77	14.27
1.09	3.71	13.53
1.19	3.78	7.9
1.28	3.72	14.53
1.49	3.87	13.43
1.67	4.43	9.16
1.57	4.44	8.93
1.6	4.31	8.71

**Table 3: The efficiency values of OE Buoy measured during the test campaign**